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A MEMS-based Double-layer Spiral Planar Inductor using Patterned Permalloy filled with Ferrite/Polyimide Composite Materials as Magnetic Layers

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Abstract. A MEMS-based planar inductor with double-layer spiral coil structure is developed in this study. The patterned permalloy which blank are filled with MnZn ferrite/PI composite materials is used as the magnetic layer of the inductor as well as the magnetic shielding layers. The double-layer planar inductor has a size of 1.5×1.5×0.15mm consisted of 13-turn spiral Cu coil for each layer and a 20-μm-thick patterned permalloy magnetic layers filled with MnZn ferrite/PI composite materials above and below. The inductor shows a higher inductance than the traditional planar inductor. The patterned permalloy made the inductor more stable in high frequency than the none-patterned. And the filling MnZn ferrite/PI composite materials made the inductor to achieve more excellent insulation and lower dissipation characteristics. And the inductor has an inductance of 1.3μH and quality factor of 2.8 at 1.5MHz.

1. Introduction

On-chip spiral inductors have played an increasingly important role in integrated circuits, such as converters, filters, mixers, and oscillators [1]. Due to the widespread use in the wireless communications technology and the strongly desire of smaller size for integrated packaging, the planar spiral inductors have gained interest in this area. The challenge of integrating inductors on-chip have stood the way of fully integration of many electronic systems such as power converter devices [2]. In the current inductive elements market, the conventional large size winding coils are still dominant. However, there have been increased efforts to reduce the size of inductor without sacrificing the performance. Planar spiral structures are often desirable for inductors because the parallelized fabrication processes can make it easy for packaging while the spiral configurations can ensure the number of turns in a very small size.

The size of the inductor can be reduced by MEMS technology. The development of MEMS technology make it possible to fabricate the planar spiral micro-inductors by some micro-fabrication processes like photolithography, wet etching, electroplating technique, etc. And the performance should be insured while used in the packaging. In recent years, there have been significant efforts to boost the inductance value by adopting the sandwich structures using magnetic shielding layers. Permalloy is a kind of soft magnetic materials with high relative permeability. It shows great compatibility with MEMS technology and plays significant role in increasing the inductance and quality factor of planar spiral inductors [3]. The permalloy magnetic films are often deposited above and below the spiral plane using the photolithography and electroplating techniques. In addition, It has been reported that MnZn ferrite material has higher saturation flux density and initial

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permeability than NiZn ferrite. MnZn also shows negligible electrical conductivity which is desirable for high frequency magnetic devices, thus eddy current losses can be neglected [4]. But MnZn ferrite usually requires high sintering temperature (1000 to 2000ºC) [5], which is not compatible with micro-fabrication processes. This challenge can be solved by using the composite materials consisting of ferrite powder and viscous polymer to form composite film, which offers a good compromise between the high permeability and high resistivity [6][7].

Now the plane sandwich structure are greatly applied in fabricating micro-inductor due to its stability and small size and compatibility with processing procedure. The metal layers of the sandwich structure can prevent the magnetic field lines from spreading outside and thus keep the magnetic field loops around the conductor lines. However, this structure will introduce high ac conductor losses and high eddy currents. Patterned permalloy which blank are filled with MnZn ferrite/PI composite materials can solve this problem effectively. As the magnetic shielding layers, appropriate patterned method can also reduce the eddy currents while it play a role in shielding the magnetic field lines outside. And the filling MnZn ferrite/PI composite materials made the inductor to achieve more excellent insulation and lower dissipation characteristics.

This study aimed to get a high inductance value in a small device size. A double-layer planar inductor with up and below patterned permalloy magnetic shielding layers filled with MnZn ferrite/PI composite materials have been fabricated. The patterned permalloy figure which the blank of the permalloy are perpendicular to the coil inside have been proved better than other figures. The inductor with a small device size of 1.5×1.5×0.15mm can been packaged easily. And the inductor has an inductance of 1.3μH and quality factor of 2.8 at 1.5MHz.

2. Inductor Design

2.1. The Structure of the Inductor

Planar, rectangular spiral geometry was chosen as a well-tested technique for maximizing inductance per area, and a nominal inductor size of 1.5mm × 1.5mm was selected. within these parameters, The number of turns was varied as an inductance vs. coil resistance tradeoff. However, a 13-turn design was qualitatively selected as a most likely candidate for fabrication and integration and all extended characterization was performed with 13-turn inductors by simulation. Single-layer coils are easy to fabricate, but the multi-layer coils have more coil turns without increasing the device size [5]. All the above factors and the microfabrication processes considered, Figure 1(a) shows the illustrated structure designed of the planar spiral inductors [7]. Double-layer structure is adopted and each coil layer consists of 13 turns. Each turn is 20μm in width and each coil spacing is 20μm. The area of the inductor is 1.5mm×1.5mm except the two metal test pads. The part of via connects the coil layers effectively above and below to form a double-layer structure. The thickness of each layer is 20±2μm and the two layers are 10±2μm apart from each other. And the above and below layers are permalloy magnetic layers which play a role in shielding the magnetic field lines outside the inductor structure. To find the optimum permalloy pattern and bring some laws of the geometric figures, eight different patterned permalloy figures were designed and simulated. Figure 1(b) illustrated these eight geometric figures. Type7 is a reference and other pattern were started from Type8. There are two basic categories. Type3 and Type5 are which permalloy blank are perpendicular to the coil inside. And Type2 and Type4 are which permalloy blank are parallel to the coil inside. It can be seen obviously from the Figure 1(b).

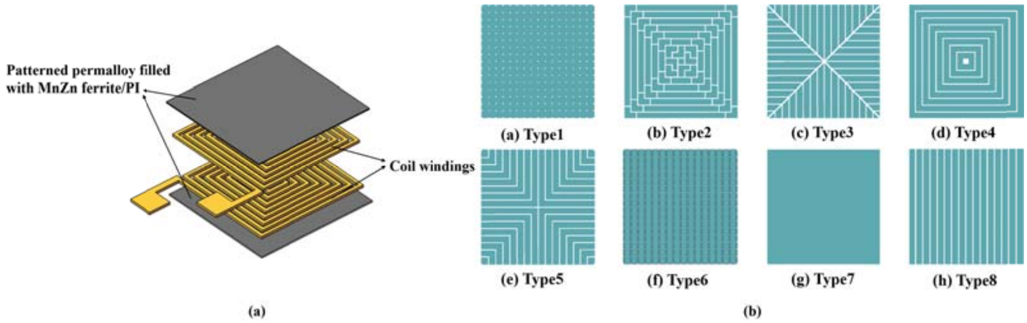

Figure 1. (a) The illustrated structure of the inductor; (b) Eight geometric figures of the patterned permalloy designed as magnetic layers.

2.2. The simulation results of the inductor

The simulation results of the inductance value *L* and the quality factor *Q* are shown in Figure 2. Figure 2(a) shows that the inductor with the patterned permalloy of Type 2, Type 4 and Type 6 do not show a better inductance value than the others. In addition, the inductor of Type 1 and Type 7 are unstable in high frequency. At 1.5MHz, the comparison of the inductance value *L* is Type5>Type3>Type8, and the Type3 shows a better stability than the Type5. Figure 2(b) shows that the maximum value of the quality factor *Q* are in the comparison of Type3>Type5>Type2>Type6> Type8>Type4>Type1>Type7. And the corresponding frequency *f* of the maximum value *Q* are in the comparison of Type4>Type2>Type6>Type3>Type5>Type8>Type1>Type7.

According to the simulation results above, the final designed inductor structure with patterned permalloy is shown in Figure 3. The Type3 and Type 5 pattern are chosen due to their excellent properties in the simulation results. And the Type 7 is chosen to be a reference object. The coil inside was a double-layer spiral planar inductor and each coil layer consists of 13turns. The size of the inductor is 1.5mm×1.5mm.

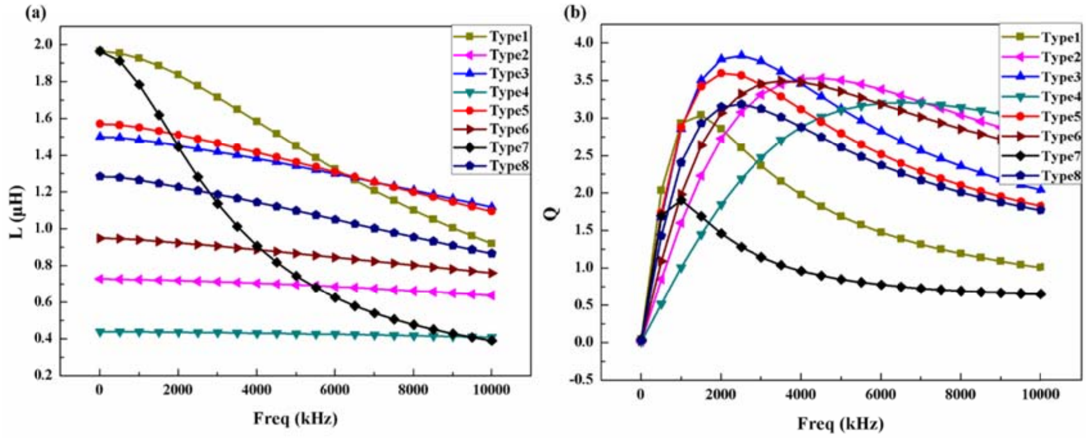

Figure 2. Simulated results of the eight types. (a) Variation of the inductance value with the frequency; (b) Variation of the quality factor with the frequency.

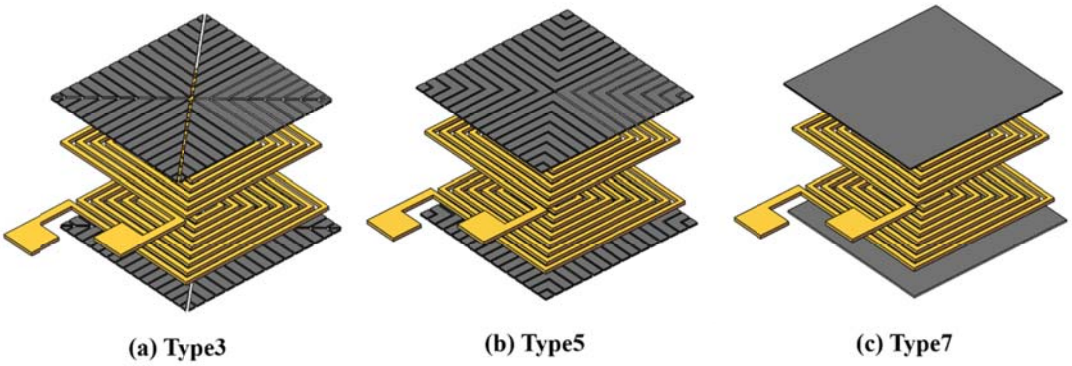

Figure 3. Schematic diagram of the experimental inductors. Type3, Type5 and Type7 are chosen according to the simulated results.

2.3. The MnZn Ferrite/PI Composite Materials Filled in the Permalloy Blank

Simulation was performed for polyimide(PI) and MnZn ferrite insulation, respectively, to compare their magnetic flux density, the magnetic field, the magnetizing inductance, and the quality factor. All the analysis are made in the frequency domain with range 10kHz -10MHz and the winding is supplied by a constant voltage of 5V. The model is completely drawn using COMSOL graphical tool and it is parameterized allowing a more flexibility and the material used are summarized in the table 1 [8].

Table 1. The material used in the simulation.

Material	Relative Permeability μ_r	Electrical conductivity σ (S/m)
Air	1	1
Copper	1	5.998e7
Polyimide	1	1
Ferrite	3000	1

Part of the simulation images were shown in Figure 4. Figure 4 (a) and (b) showed that the magnetic flux density of the coil with ferrite insulation layer was more uniformly distributed than that with polyimide. The magnetic field in the space of figure 4 (b) was disorderly compared with that figure 4 (a). The distribution of the magnetic flux densities around the coils in the direction vertical to the coil plane were also shown in figure 4 (c) and (d), respectively. It was found that the MnZn ferrite insulation made the magnetic flux concentrated inside the Cu coil. As shown in figure 4 (d), the magnetic flux density in the air space was almost zero, which indicated a low magnetic leakage. However, the PI insulation had more serious magnetic leakage in the air space than the ferrite insulation, as shown in figure 4 (c). It can be concluded that the MnZn ferrite efficiently suppressed the magnetic flux from spreading out and decreased the magnetic leakage flux. According to the simulation results, the ferrite magnetic insulation could decrease the magnetic leakage flux and increase the magnetic loops. As a result, it reduced the eddy current losses and increased the overall performance of an inductor. So the filling MnZn ferrite/PI composite materials made the inductor to achieve more excellent insulation and lower dissipation characteristics.

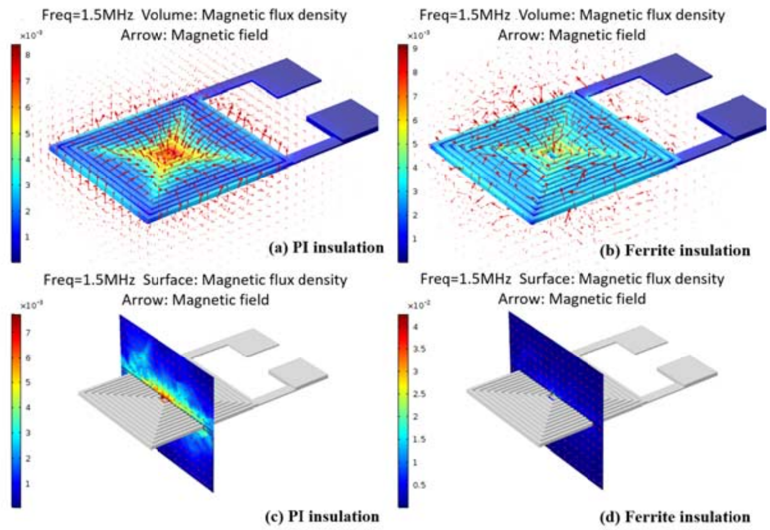

Figure 4 (a-b) 3D graph of the magnetic field and the magnetic flux density; (c-d) Magnetic flux density around the coils in the direction vertical to the coil plane; (a) and (c) are PI insulation, while (b) and (d) are MnZn ferrite insulation.

3. Fabrication Procedure

The permalloy magnetic films are deposited above and below the spiral plane using the photolithography and electroplating techniques. For MnZn ferrite/PI composite materials insulation, the ferrite powders with an average particle size of 10μm were used as precursor. The ferrite powder, a little PI and diluting agent were mixed by ball-milling process to make sure the ferrite powder fully dispersed in the polyimide. Then the ferrite/PI composite was spin coated and solidified on the patterned permalloy as an insulation layer with magnetic property. The Cu windings was prepared on a 1mm thickness glass substrate by electroplating process. The photoresist was spin coated on the electroplated Cu film, and patterned using photolithography and wet etching [9]. Then the spiral Cu conductor line was obtained. The main fabrication processes of the double-layer spiral planar inductor are illustrated in the Figure 5. The double-layer structure was realized by a through-hole filled with Cu connecting two layers of Cu coil [10]. The second coil layer is electroplated after the spin-coating. The via connected the upper and lower coil and the distance between the two coil layers was designed as 10μm. The pictures of the inductor samples fabricated by some MEMS technology are shown in Figure 6.

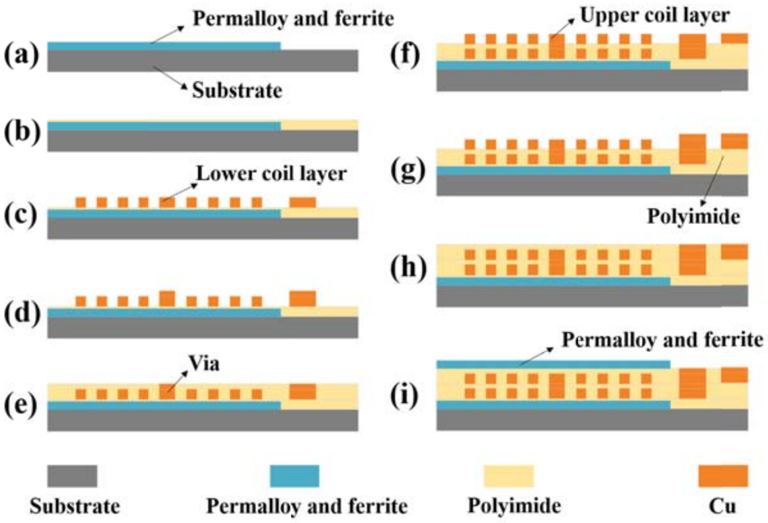

Figure 5. Main fabrication processes (a)-(i).

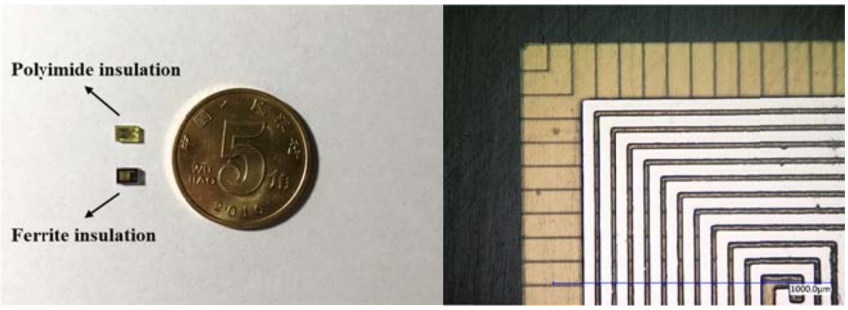

Figure 6. Fabricated inductor samples.

4. Results and Discussion

The static magnetic parameters of the ferrite powder were summarized in table 2. These parameters are provided by the powder merchant.

Table 2. Main magnetic parameters of the MnZn ferrite powder.

Saturation flux density	Initial magnetic permeability	Squareness ratio	Coercive force(A/m)
510	3300	11	13

Figure 7 showed the relationship between the inductance *L* and the quality factor *Q* with the frequency at a testing voltage of 5V. The testing frequency range was 10kHz-10MHz. All the testing results are from the inductor with the patterned permalloy of Type 3, Type 5 and Type 7. Figure 7(a) shows that the inductor of Type 7 is unstable in high frequency. At 1.5MHz, the comparison of the inductance value *L* is Type 7>Type 5>Type 3, and the Type3 shows a better stability than the Type5. Figure 8(b) shows that the maximum value of the quality factor *Q* are in the comparison of Type 3>Type 5>Type 7. And the corresponding frequency *f* of the maximum value *Q* are in the comparison of Type 3>Type 5>Type 7. The trend is achieved agreeable to the simulated results.

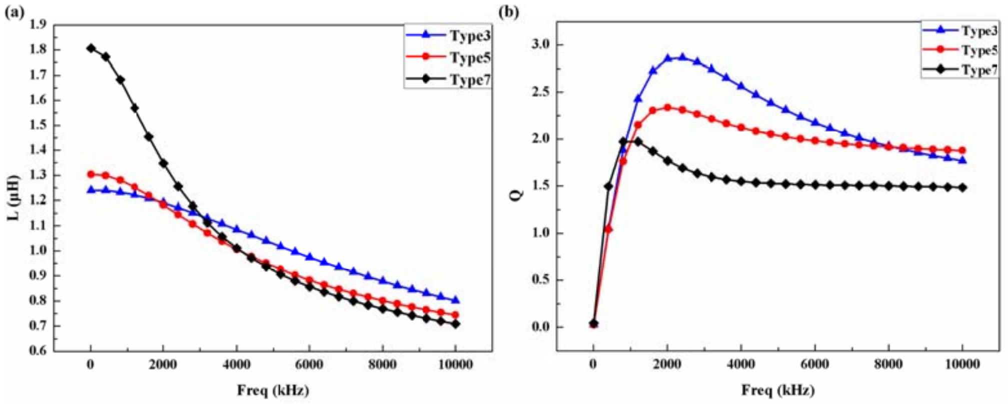

Figure 7. Experimental data of the chosen three types of the planar inductors with patterned permalloy magnetic layers filled with MnZn ferrite/PI composite materials. (a) Relation between inductance L and frequency; (b) Relation between the quality factor Q and frequency.

5. Conclusion

In conclusion, the MEMS-based spiral-type double-layer planar inductor was designed, simulated, fabricated and tested. The optimum patterned permalloy which blank are filled with MnZn ferrite/PI composite materials is used as the magnetic layer of the inductor as well as the magnetic shielding layers. The results indicated that the patterned permalloy made the inductor more stable in high frequency than the none-patterned. And the filling MnZn ferrite/PI composite materials made the inductor to achieve more excellent insulation and lower dissipation characteristics. In this study, the novel structure inductor have been fabricated by some MEMS technologies. And it had an inductance of 1.3μH and quality factor of 2.8 at 1.5MHz. It will have many potential applications in magnetic sensors and actuators, and electronic circuit components.

Acknowledgements

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